IMPACTS OF HIGHER-ORDER DISPERSION COEFFICIENTS AND DISPERSION FLUCTUATIONS ON ONE-PUMP FIBER OPTICAL PARAMETRIC AMPLIFIER

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To my beloved family

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ABSTRACT

Four-wave mixing (FWM) is a nonlinear effect in optical fiber which is useful for fiber optical parametric amplifiers (FOPA). The performance of FOPA i.e. parametric gain, amplification bandwidth, and saturation power are reliant on the efficiency of the FWM process. The random dispersion fluctuations ($\delta\beta$) and higher-order dispersion coefficients ($\beta_{2m}, m = 1, 2, 3$) are two factors that contribute to the FWM efficiency. Since this two factors cannot be avoided in practice, this dissertation thus presents analytical and numerical simulation works that associated with the impact of $\delta\beta$ and β_{2m} on the performance of one-pump (1-P) FOPA. As for numerical approach, three-coupled amplitude equations with fiber losses were solved using the Runge-Kutta-Fehlberg method for the calculation of the pump, signal, and idler, then the parametric gain. Meanwhile, for analytical approach, a derivation was performed from the coupled equations to govern parametric gain expression. Using the aforementioned methods, three primary research studies were successfully simulated. The first study is related to the identification of optimum parameters' value in efforts to enhance the parametric gain spectrum. The optimum parameters' value are identified as 500 m of fiber-length, 30 dBm of input pump power and 1.5 nm distance between pump and zero-dispersion wavelength. Meanwhile, for dispersion slope, β_4, and β_6, the optimum values are 0.01 ps/nm^{2}km, 6.23×10^{-5} ps^4/km and 1.18×10^{-8} ps^6/km, respectively. The second simulation work is associated to the sign combination of β_2, β_4 and β_6. It is shown that the combination of $\beta_2 < 0$, $\beta_4 > 0$ and $\beta_6 > 0$ results in optimum gain spectrum. The third study is related to the impact of $\delta\beta$ and β_{2m} on the 1-P FOPA performances. The increase of amplitude of $\delta\beta$ has reduced the peak gain, increased the total bandwidth and saturation power, whereas the increase of β_{2m} has increased the 3 dB-bandwidth and reduced the saturation power while the peak gain remain unchanged. These analyses are useful for the case where the signal wavelength is detuned far ($>$ 100 nm) from the pump wavelength, such as in the optical fiber communication link.

ABSTRAK

Pergaulan empat-gelombang (FWM) ialah kesan tidak linear dalam gentian optik yang sangat berguna kepada penguat parametrik gentian optik (FOPA). Prestasi FOPA seperti nisbah parametrik, lebar jalur penguatan dan kuasa tepu bergantung pada kelancaran proses FWM. Faktor yang menyumbang kepada kelancarannya adalah perubahan rawak penyebaran ($\delta\beta$) dan peringkat-lebih-tinggi pekali penyebaran (β_{2m}, $m = 1, 2, \ldots$) dalam gentian optik. Disebabkan $\delta\beta$ dan β_{2m} gagal dielakkan dalam situasi sebenar, maka kajian simulasi analitikal dan berangka dijalankan untuk menganalisis impak $\delta\beta$ dan β_{2m} terhadap prestasi satu-pam (1-P) FOPA. Bagi kaedah berangka, persamaan amplitud bergabung-tiga dengan kehilangan gentian diselesaikan menggunakan kaedah Runge-Kutta-Fehlberg untuk mendapatkan amplitud pam, isyarat, frekuensi baharu iaitu *idler* dan nisbah parametrik. Kaedah analitikal pula mengkamirkan persamaan amplitud bergabung-tiga bagi menerbitkan sebutan nisbah parametrik. Tiga kajian penyelidikan telah berjaya disimulasi dengan menggunakan dua kaedah tersebut. Kajian pertama adalah mengenal pasti nilai optima parameter 1-P FOPA dalam usaha menambah baik spektrum nisbah parametrik. Nilai optima parameter yang dikenal pasti adalah panjang gentian optik iaitu sepanjang 500 m, kuasa pam setinggi 30 dBm, dan 1.5 nm jarak antara panjang gelombang pam dan penyebaran-sifar. Sementara itu, bagi penyebaran cerun, β_4, dan β_6, nilai optimum masing-masing adalah 0.01 ps/nm^{2}km, 6.23×10^{-5} ps^4/km dan 1.18×10^{-8} ps^6/km. Kajian kedua berkaitan gabungan tanda antara β_2, β_4 dan β_6. Dapatan kajian menunjukkan gabungan antara $\beta_2 < 0$, $\beta_4 > 0$ dan $\beta_6 > 0$ menghasilkan spektrum nisbah parametrik yang optima. Kajian ketiga pula tentang kesan $\delta\beta$ dan β_{2m} terhadap prestasi 1-P FOPA. Kenaikkan amplitud $\delta\beta$ telah mengurangkan nisbah parametrik optima, menaikkan lebar jalur dan kuasa tepu, manakala kenaikkan β_{2m} pula telah melebarkan jalur-3 dB dan mengurangkan kuasa tepu. Analisis ini bermanfaat apabila panjang gelombang isyarat ditetapkan jauh (> 100 nm) daripada panjang gelombang, seperti didalam rantaian komunikasi gentian optik.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_{eff}	-	Effective area
A_i	-	Idler amplitude
A_p	-	Pump amplitude
A_s	-	Signal amplitude
A_i^*	-	Complex conjugate of A_i
A_p^*	-	Complex conjugate of A_p
A_s^*	-	Complex conjugate of A_s
c	-	Speed of light in vacuum
$c.c.$	-	Complex conjugate
D	-	Chromatic dispersion
D_λ	-	Dispersion slope at λ
f	-	Dimensionless physical constant
g	-	Gain coefficient
G	-	Parametric gain
$\bar{G}$	-	Average parametric gain
L	-	Fiber-length
L_c	-	Correlation length
n	-	Refractive index
n_0	-	Linear refractive index
n_2	-	Nonlinear refractive index coefficient
N	-	Number of segments
P_{NL}	-	Nonlinear polarization
P_{p0}	-	Input pump power
P_{s0}	-	Input signal power
α	-	Fiber loss
β	-	Wave vector

β_2	-	Second-order dispersion coefficient
β_{2m}	-	Higher-order dispersion coefficient
β_4	-	Fourth-order dispersion coefficient
β_6	-	Sixth-order dispersion coefficient
$\chi^{(j)}$	-	jth-order susceptibility
$\chi^{(1)}$	-	Linear susceptibility
$\chi^{(2)}$	-	Second-order susceptibility
$\chi^{(3)}$	-	Third-order susceptibility/nonlinear effect
χ_{L}	-	Linear susceptibility
χ_{NL}	-	Nonlinear susceptibility
$\delta\beta$	-	Random dispersion fluctuations
$\delta\omega$	-	Frequency chirp
$\Delta\beta$	-	Linear phase-mismatch
$\overline{\Delta\beta}$	-	Average value of $\Delta\beta$
$\Delta\omega$	-	Angular frequency difference between ω_{P} and ω_{s}
ε_0	-	Vacuum permittivity
γ	-	Fiber nonlinearity
K	-	Total phase-mismatch
λ	-	Wavelength
λ_p	-	Pump wavelength
λ_s	-	Signal wavelength
λ_0	-	Zero-dispersion wavelength
μ_0	-	Vacuum permeability
ω	-	Frequency
ω_i	-	Idler frequency
ω_{P}	-	Pump frequency
ω_{s}	-	Signal frequency
ω_0	-	Zero-dispersion frequency
Ω	-	Angular frequencies difference
ϕ	-	Phase shift
ϕ_{NL}	-	Nonlinear phase shift
σ	-	Fluctuation amplitude

σ_0	-	Conductibility
1-P	-	One-pump
2-P	-	Two-pump
CW	-	Continuous-wave
DSF	-	Dispersion-shifted fiber
EDFA	-	Erbium-doped fiber amplifier
FOPA	-	Fiber optical parametric amplifier
FWM	-	Four-wave mixing
HNL-DFF	-	Highly-nonlinear dispersion-flattened fiber
HNL-DSF	-	Highly-nonlinear dispersion-shifted fiber
HNLF	-	Highly-nonlinear fiber
MCVD	-	Modified chemical vapor deposition
NLSE	-	Nonlinear Schrödinger equation
OFS	-	Optical Fiber Solution (a Furukawa company)
OPM	-	Optical power meter
OSA	-	Optical spectrum analyzer
OVD	-	Outside vapor deposition
PC	-	Polarization controller
PCF	-	Photonics crystal fiber
PL	-	Pump laser
PM	-	Phase modulator
QPM	-	Quasi-phase matching
SBS	-	Stimulated Brillouin scattering
SL	-	Signal laser
SPM	-	Self-phase modulation
SRS	-	Stimulated Raman scattering
TBPF	-	Tunable bandpass filter
THG	-	Third harmonic generation
TLS	-	Tunable laser source
WDM	-	Wavelength-division multiplexing
XPM	-	Cross-phase modulation
ZDW	-	Zero-dispersion wavelength

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CHAPTER 1

INTRODUCTION

This chapter devotes to the background of fiber optical parametric amplifier (FOPA). In addition, it also discusses the problem statements as well as the research objectives along with the research scopes. Thesis outline is offered at the end of this chapter in order to provide an overview of the thesis structure.

1.1 Background

Fiber amplifiers development started in the 1970s. The development started off as a solution to solve a telecommunications issue associated with the data or signal transmission. Figure 1.1 illustrates an optical fiber communication link. The basic function of an optical fiber link is to transmit a signal from communication equipment at one location to corresponding equipment at another location [1]. Transmission for long distances which requires a signal to be amplified between different spans of transmission lines. The ability of optical fiber amplifiers to perform direct signal

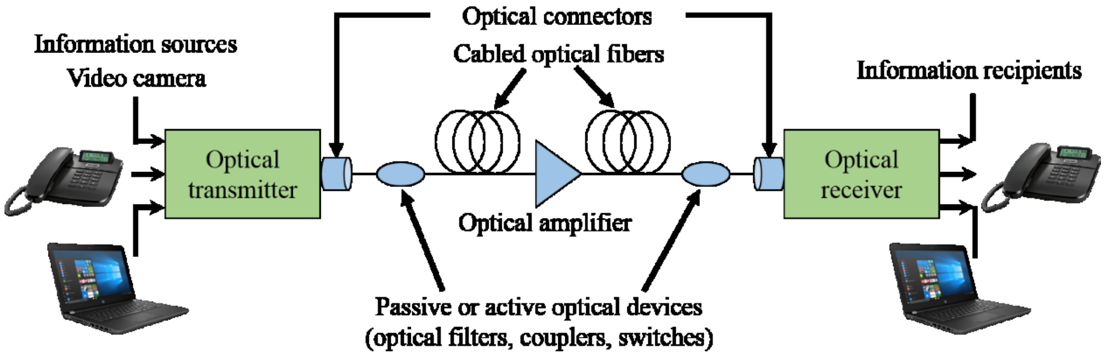

Figure 1.1: Optical fiber communication link [1]

amplification have substituted a much more complex technology especially the one that is based on electronic detection. This progression turns out to be one of the significant foundations for enormous expansion of the transmission capacity, thereby also for the internet.

These days the optical communication systems demand for fiber amplifiers that are competent not only to amplify the signal, but as well as flexibility in terms of shape of the gain spectrum and its center frequency. The only fiber amplifier that offers such advantages is a FOPA. Generally, there are two types of FOPA, known as one-pump (1-P) FOPA and two-pump (2-P) FOPA, which are illustrated in Figure 1.2(a) and Figure 1.2(b), respectively. 1-P FOPA use one pump source at their input, whereas in 2-P FOPA two pump sources with different wavelengths are used at their input [2].

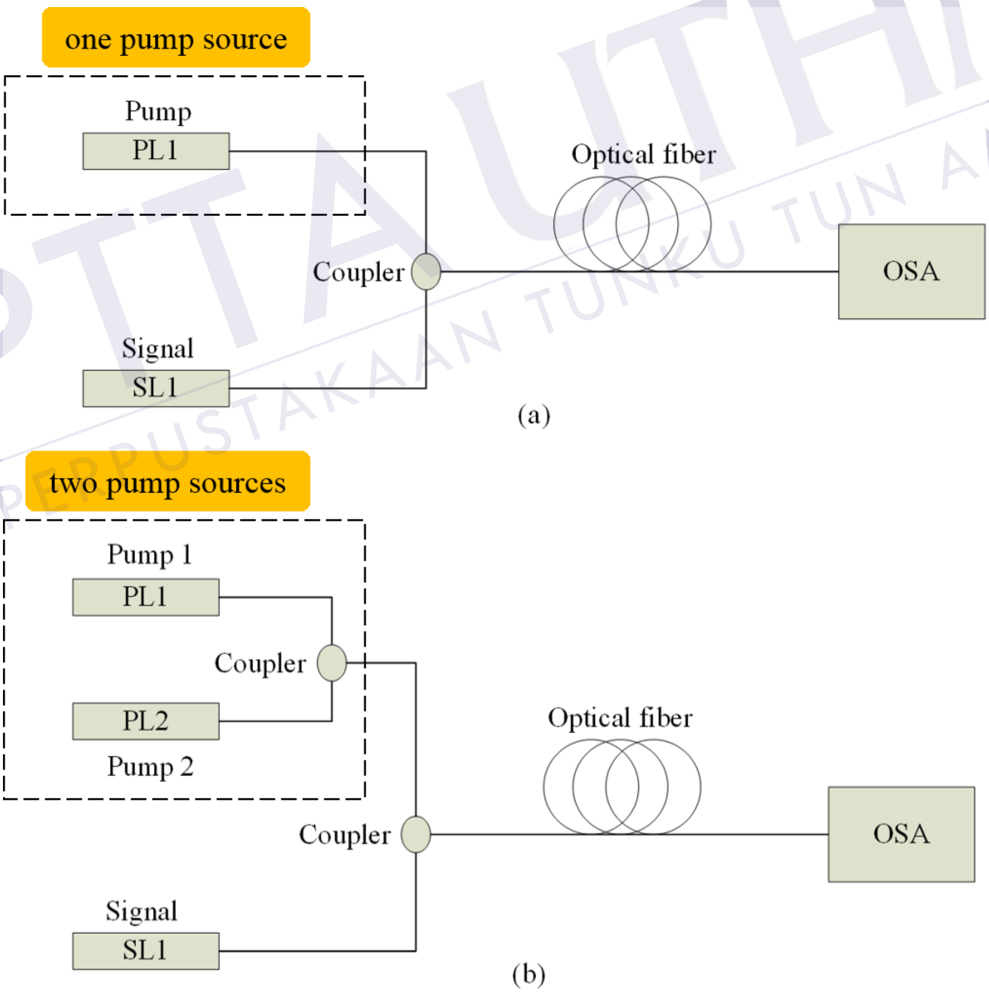

Figure 1.2: Basic setup of (a) 1-P FOPA and (b) 2-P FOPA. PL1: pump laser 1, PL2: pump laser 2, SL1: signal laser 1, and OSA: optical spectrum analyser

Since the FOPA is a four-wave mixing (FWM)-based device, it has huge potential as the wavelength conversion [3]–[8], and phase conjugation [9]–[13]. Besides that, amplification in FOPA is attended with low noise i.e. 0 dB and 3 dB as it works in the phase-sensitive and phase-insensitive mode, correspondingly [14]–[16]. The FOPA advantages in term of its adjustable gain spectra and center frequency is already surpassed the limitation of conventional fiber amplifiers i.e. Raman amplifier and erbium-doped fiber amplifier (EDFA). Besides that, the ability of FOPA to operate in saturation regimes where the signal power is not small, has made it a versatile parametric amplifier. Among the interesting applications that have been found for FOPA in saturation regimes are all-optical limiters [17]–[20], noise suppression [21]–[24], signal regeneration [25]–[29], and pulse generation [30]–[34]. In addition, besides network system, FOPA can also be applied in industrial material processing. For instance, the gain-saturated (high signal power) FOPA can be implemented in a high-power fiber laser, in which can be used for various applications, e.g. laser marking, engraving, cutting, ablation, welding, drilling and 3D printing.

Generally, a practical 1-P FOPA supposes to demonstrate an optimum parametric gain spectrum i.e. high gain and wide amplification bandwidth. The optimum parametric gain spectrum possibly be realized by altering the amplifier parameters. The amplifier parameters such as input pump power and position of pump wavelength with respect to zero-dispersion wavelength (ZDW), are most likely to affect the resulting parametric gain spectrum [35], [36]. On top of that, the parametric gain spectrum is also affected by the dispersion properties of its gain medium i.e. dispersion slope and higher-order dispersion coefficients of the optical fiber [37], [38]. Another parameter that affects the parametric gain spectrum is fiber-length [39]. Theoretically, the longer fiber-length results in a high parametric gain, yet suffering from the broken phase-matching. This means the optimum gain spectrum cannot simply be obtained by extending the fiber-length. Therefore, the appropriate way is by identifying a practical optimum value of the fiber-length so that the resulting parametric gain spectrum can be optimized. This is also applied to other parameters.

As optical fiber is a gain medium of the FOPA, its dispersion characteristics will somehow affect the efficiency of signal amplification. This involves both the random dispersion fluctuations and higher-order dispersion coefficients of the optical fibers. The dispersion of pulses along the optical fiber cannot be avoided as they are dealing with phase-shift and group delay phenomena [1]. Apart from that, the fiber imperfection during the fabrication process is also one of the causes. The asymmetry of a fiber over its length is in random style depending on the fabrication technique e.g. the modified chemical vapor deposition (MCVD) and outside vapor deposition (OVD) [40], [41]. The imperfections during the fabrication process consequently arise the random dispersion fluctuations along the fiber-length, which then affects the amplification process of FOPA. Since the dispersion phenomena in the optical fiber cannot be avoided, thus it is imperative to investigate its effects and limitations on the FOPA performance.

1.2 Problem statement

In view of investigating the performance of 1-P FOPA, a few principal problems were identified in this study. The problems identified here were acquired from the literature review that was carried out during the study and they provide a basis for the objectives of this thesis.

Most of previous works were focusing on special fiber such as lead-silicate binary multi-clad microstructured fiber, tellurite hybrid microstructured fiber, and photonic crystal fiber while ignoring their losses. Those aforementioned optical fibers are not practical for optical fiber communication link since they have very high losses due to the complex geometrical parameters. Owing to a simple geometrical structure, highly-nonlinear dispersion-shifted fiber (HNL-DSF) is an ideal gain medium for 1-P FOPA. Thus, identification of optimum parameters' value specifically with HNL-DSF characteristics need to be conducted.

The higher-order dispersion coefficients of an optical fiber have been proven to be vital in obtaining the desired amplification bandwidth [37]. The involvement of dispersion coefficients up to sixth-order shows significant improvement of the amplification bandwidth [38]. However, the signs of these coefficients are needed to be well combined or else it will result in a substandard parametric gain spectrum. Yet in some cases, regardless of its sign, the sixth-order dispersion coefficient of an optical fiber does not significantly affect the amplification bandwidth. Therefore, it is substantial to specifically examine the impact of signs' combination of the second-order, fourth-order, and sixth-order dispersion coefficients for the HNL-DSF. This analysis will, later on, determine whether the sixth-order dispersion coefficient should be taken into account or not.

In reality, the ZDW fluctuates throughout the fiber-length. This is due to random impairments and asymmetries of the fibers. The fluctuations will affect the phase-matching condition between the interacting waves, and this will influence the performance of 1-P FOPA. The impact of ZDW fluctuations on the performance of the 1-P FOPA was previously studied [42]–[46]. However, those studies were limited for the case of the small-signal regime in which the signal power utilized was small e.g. -40 dBm. In addition, they treated the pump as undepleted, where the pump power was considered constant along the fiber-length. In those studies, three-coupled amplitude equations for the pump, signal, and idler were simplified, and they were then solved using matrix approach. However, such a matrix approach is not accurate for the saturation regime in which the signal power utilized was relatively large [47]. Thus, a numerical approach was proposed in [47] in order to cater for the case of large signal power analysis. Despite the enhancement, the approach was limited to the second-order dispersion coefficient. In other words, higher-order dispersion coefficients were ignored, and this can be inaccurate, especially when the signal wavelength is detuned far enough from the pump wavelength.

1.3 Research objectives

The aim of this research is to investigate the impact of higher-order dispersion coefficients and random dispersion fluctuations on the 1-P FOPA performance. Specific objectives are as follow:

i. To identify the optimum values of fiber-length, input pump power, distance of pump wavelength with respect to ZDW, dispersion slope, higher-order dispersion coefficient, and the optimum parametric gain spectrum, in a HNL-DSF of Optical Fiber Solutions (OFS) company with fiber loss of $\alpha = 0.82$ dB/km, nonlinearity of $\gamma = 11.5$ $W^{-1}km^{-1}$ and ZDW at $\lambda_0 = 1556.5$ nm.

ii. To examine the impact of higher-order dispersion coefficients signs (negativity/positivity) of a HNL-DSF on amplification bandwidth.

iii. To simulate the effect of higher-order dispersion coefficient and random dispersion fluctuations of a HNL-DSF on the parametric gain spectrum and saturation power.

1.4 Research scope

The scopes of this research work are generally illustrated in Figure 1.3. This research concentrates only on 1-P FOPA. The 1-P FOPA is investigated in terms of its performances of parametric gain, amplification bandwidth and saturation power. In addition, these performances are observed in small-signal and saturation regimes. The gain medium of 1-P FOPA is a HNL-DSF of OFS company. Theoretically, only even-order dispersion coefficients are affecting the parametric gain spectrum especially the performance of amplification bandwidth. Following the Taylor series expansion, the even-order dispersion coefficient can possibly be extended infinitely i.e. β_{2m}, $m = 1, 2, \cdots, \infty$. However, this work only considers the higher-order dispersion coefficients

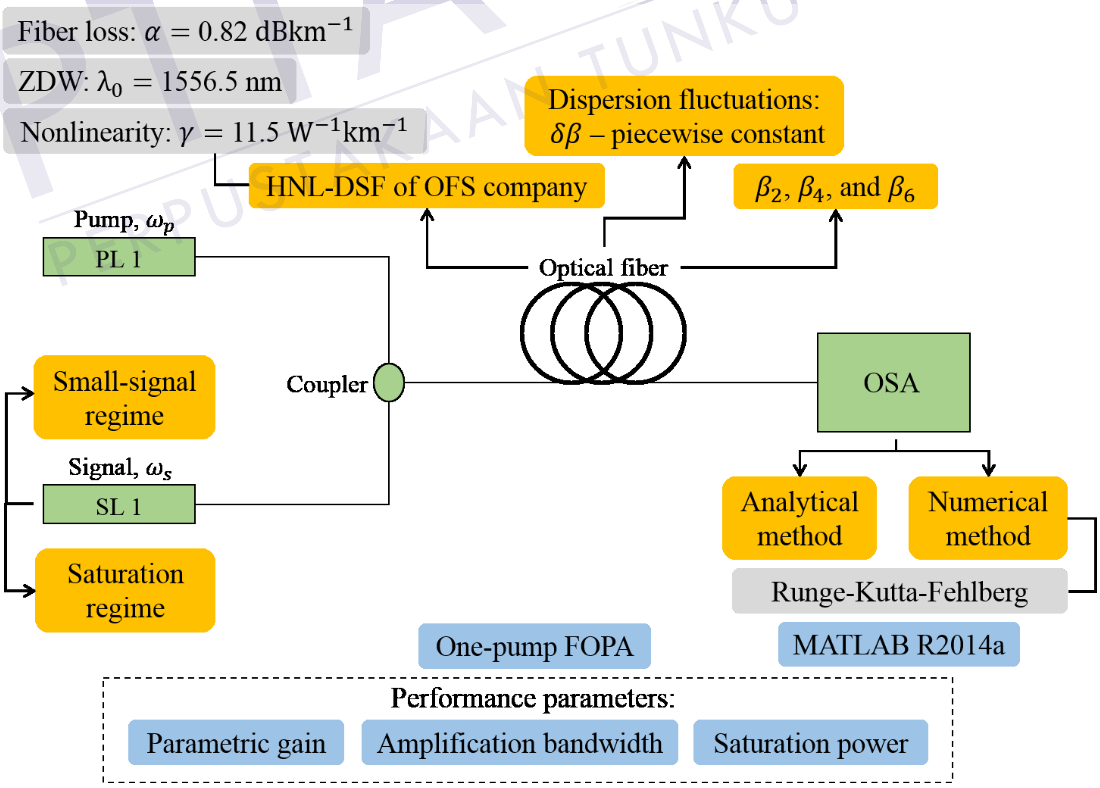

Figure 1.3: Illustration of research scopes

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